Distribution of Blackbody Cavity Radiation in a Moving Frame of Reference*

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Blackbody cavity radiation is considered from the point of view of an observer in arbitrary uniform motion with respect to the c.m. of the radiation. It is found that the only effect of the motion is to introduce an angle-dependent effective temperature, which replaces the rest-frame temperature of the cavity. The results are applied to the question of the earth's motion through the 3°K cosmic radiation.

I. INTRODUCTION

THE discovery that the universe is apparently filled with 3°K blackbody cavity radiation[1] leads to the interesting possibility of detecting motion with respect to the c.m. of this radiation.[2] In order to discuss this question we compute the blackbody distribution as seen by an observer in arbitrary uniform motion with respect to the radiation.[3] General results are obtained, which are then easily specialized to the situation of primary interest for the 3°K cosmic radiation, where the observer's speed is much less than that of light.

In Sec. II the notation is established. A derivation of the photon distribution in a moving reference frame is presented in Sec. III. In Sec. IV the stress-energy tensor is discussed, and the results of Sec. III are shown to be consistent with the transformation properties of the stress-energy tensor. Some comments on temperature are made in Sec. V. Specialization to the 3°K cosmic radiation is carried out in Sec. VI, and concluding remarks are made in Sec. VII.

II. NOTATION

We will be concerned with two frames of reference, s and s', shown in Fig. 1. The frame s' is taken to be at rest with respect to the blackbody radiation, and the frame s moves in the direction of the positive z' axis with speed[4] βc. We wish to describe the blackbody radiation in the frame s.

In the rest frame s' the radiation may be specified by the photon distribution[5]

$$d^3N'=\frac{\omega'^2}{4\pi^3c^3}\frac{d\omega' d\Omega' dV'}{\exp(\hbar\omega'/kT')-1},\tag{2.1}$$

where standard definitions are used, i.e., $\hbar$ is Planck's constant divided by 2π, T' is the temperature of cavity, k is Boltzmann's constant, ω' is the circular frequency of photon, $d\Omega'$ is the element of solid angle, and dV' is the element of volume.

The primes of course refer to the rest system s'. Physically, d^3N' represents the number of photons in the frame s' within the volume dV', the frequency range $d\omega'$, and the solid angle $d\Omega'$, at one instant of time t' in s'. The corresponding energy is simply

$$d^3E'=\hbar\omega' d^3N'.\tag{2.2}$$

We wish to determine the distributions corresponding to Eqs. (2.1) and (2.2) in the moving frame s.

III. BLACKBODY DISTRIBUTION IN A MOVING FRAME OF REFERENCE

In this section, a derivation of the d^3N distribution in s is given. It is useful first to derive various transformation rules for a single photon.

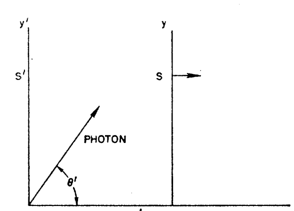

FIG. 1. The two frames of reference considered. s' is the rest frame of the radiation; s moves along $+z'$ in s', with speed βc.

A. Lorentz Transformations for a Single Photon

We consider a photon of frequency ω', with its velocity at an angle θ' with respect to the z' axis, as shown in Fig. 1. Any four- vector A_μ' in s' is given in s by

$$A_\mu=L_{\mu\nu}A_\nu',\tag{3.1}$$

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†‡ National Science Foundation Predoctoral Fellow.

[1] R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. **142**, 414 (1965); A. A. Penzias and R. W. Wilson, *ibid.* **142**, 419 (1965); P. G. Roll and D. T. Wilkinson, Phys. Rev. Letters **16**, 405 (1966); T. F. Howell and J. R. Shakeshaft, Nature, **210**, 1318 (1966); G. B. Field and J. L. Hitchcock, Phys. Rev. Letters **16**, 817 (1966); P. Thaddeus and J. F. Clauser, *ibid.* **16**, 819 (1966); T. F. Howell and J. R. Shakeshaft, Nature **216**, 753 (1967); E. K. Conklin and R. N. Bracewell, *ibid* **216**, 777 (1967).

[2] R. B. Partridge and D. T. Wilkinson, Phys. Rev. Letters **18**, 557 (1967); R. K. Sachs and A. M. Wolfe, Astrophys. J. **147**, 73 (1967); J. J. Condon and M. Harwit, Phys. Rev. Letters **20**, 1309 (1968); **21**, 58 (E) (1968).

[3] Kurd von Mosengeil, Ann. Physik **22**, 867 (1907). Although some points in the derivation given in this paper are not entirely clear to the present authors, the results appear to agree with the findings of Sec. III of this paper.

[4] The speed of light is denoted by c. We use a metric such that $x_\mu=(\mathbf{x},ict)$. $(1-\beta^2)^{-1/2}\equiv\gamma$.

[5] See, e.g., Max Born, *Atomic Physics* (Hafner Publishing Company, New York, 1962), 7th ed.

with

$$L_{\mu\nu}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & \gamma & i\beta\gamma\\ 0 & 0 & -i\beta\gamma & \gamma\end{bmatrix}. \tag{3.2}$$

By considering the photon four-momentum, the frequency and polar angle of the photon in s are easily specified:

$$\omega=\omega'\gamma(1-\beta\cos\theta'), \tag{3.3}$$

$$\tan\theta=\sin\theta'/[\gamma(\cos\theta'-\beta)]. \tag{3.4}$$

Trigonometric identities yield a more useful relation between the angles:

$$\cos\theta=(\cos\theta'-\beta)/(1-\beta\cos\theta'). \tag{3.5}$$

The solid angle transformation is now easily derived from Eq. (3.5):

$$\frac{d\Omega}{d\Omega'}=\frac{d\cos\theta}{d\cos\theta'}=[\gamma(1-\beta\cos\theta')]^{-2}. \tag{3.6}$$

Finally, Eqs. (3.3)–(3.6) remain valid when primed and unprimed quantities are interchanged and the sign of β is reversed. This leads to a particularly useful identity:

$$\gamma(1+\beta\cos\theta)=[\gamma(1-\beta\cos\theta')]^{-1}. \tag{3.7}$$

B. Direct Transformation of Blackbody Distribution

We start with Eq. (2.1), but we use Eqs. (3.3)–(3.7) to express all quantities (except d^3N' itself) in s. We obtain

$$d^3N'=\gamma^2(1+\beta\cos\theta)\frac{\omega^2}{4\pi^3c^3}\times\frac{d\omega dVd\Omega}{\exp[\hbar\omega\gamma(1+\beta\cos\theta)/kT']-1}, \tag{3.8}$$

where we have also used

$$dV=dV'/\gamma. \tag{3.9}$$

Despite our use of mathematical identities to introduce quantities in s, the physical significance of d^3N' remains as it was in Eq. (2.1) i.e., d^3N' is the number of photons in the frequency range $d\omega'$, the solid angle $d\Omega'$, and the volume dV' at an instant of time t' in s'. By virtue of the transformation equations, these very photons are within the frequency range $d\omega$ and the solid angle $d\Omega$ in s. They are *not*, however, within the volume of dV at any instant of time in s.

To make this more precise, we take dV' to be a cylinder of cross section A, lying parallel to the z' axis, between $z'=0$ and $z'=a$. The d^3N' photons may now be said to be counted by an imaginary plane (perpendicular to z') which sweeps from $z'=a$ to $z'=0$ instantaneously, at $t'=0$. Every photon in $d\omega'$, $d\Omega'$ which is swept over is counted. This process is easily described in s: From the Lorentz transformation, the plane is seen to start at $z=\gamma a$ at $t=-\beta\gamma a/c$ and to finish at $z=0$, $t=0$. Thus the plane sweeps over a volume γaA with a speed c/β, in the negative z direction. Since the speed is not infinite in the system s, the volume swept over with respect to the photons depends on the velocity direction of the photons. The z component of the relative photon-plane velocity in s is given by

$$(V_{\rm rel})_z=c\cos\theta+c/\beta \tag{3.10}$$

and the volume of photons counted is then

$$\text{vol.}=A(V_{\rm rel})_z(\beta\gamma a/c)=aA\gamma(1+\beta\cos\theta). \tag{3.11}$$

This is the result desired: It means that d^3N' correspond to those photons in s which are in $d\omega$, $d\Omega$ and occupy a volume $\gamma(1+\beta\cos\theta)aA$ at an instant of time t. We now define d^3N to be those photons in s which at an instant of time t occupy a volume $dV=dV'/\gamma=aA/\gamma$

$$d^3N=d^3N'/[\gamma^2(1+\beta\cos\theta)]. \tag{3.12}$$

Combining Eqs. (3.12) and (3.8), we have

$$d^3N=\frac{\omega^2}{4\pi^3c^3}\frac{d\omega d\Omega dV}{\exp(\hbar\omega/kT_e)-1}, \tag{3.13}$$

where an angle-dependent "effective temperature" T_e has been defined as

$$T_e=T'/\gamma(1+\beta\cos\theta). \tag{3.14}$$

This striking result implies that the *only* effect of uniform motion through blackbody radiation is to alter the effective temperature, which is then dependent on the angle at which observations are made relative to the direction of motion.[6] In particular, the form of the distribution is identical to that of the rest frame, and the magnitude is precisely that associated with blackbody radiation of temperature T_e. Thus in all directions the radiation appears perfectly "black" (rather than "grey" or "hyperblack"). Observation of blackbody radiation in one direction is therefore not sufficient to determine whether the observer is in motion relative to the c.m. of the radiation.

Note added in proof. Two other derivations of these results have recently been given: C. V. Heer and R. H. Kohl, Phys. Rev. **174**, 1611 (1968); P. J. E. Peebles and D. T. Wilkinson, Phys. Rev. **174**, 2168 (1968).

IV. STRESS-ENERGY TENSOR

In this section it is shown that Eqs. (3.13) and (3.14) lead to energy density, momentum density, and momentum flux with the transformation properties required by the symmetric stress-energy tensor $T_{\mu\nu}$. In

[6] A derivation which does not invoke photons at all has been given by R. N. Bracewell and E. K. Conklin, Nature **219**, 1343 (1968).

the rest frame s' it is easily shown that $T_{\mu\nu}'$ is given by[7]

$$T_{\mu\nu}'=U'\begin{bmatrix}\frac{1}{3} & 0 & 0 & 0\\ 0 & \frac{1}{3} & 0 & 0\\ 0 & 0 & \frac{1}{3} & 0\\ 0 & 0 & 0 & -1\end{bmatrix}, \tag{4.1}$$

where the energy density in s' is denoted by U'. From the Lorentz transformation,

$$T_{\mu\nu}=L_{\mu\rho}L_{\nu\sigma}T_{\rho\sigma}'$$
$$=U'\begin{bmatrix}\frac{1}{3} & 0 & 0 & 0\\ 0 & \frac{1}{3} & 0 & 0\\ 0 & 0 & \gamma^2(\frac{1}{3}+\beta^2) & -i\frac{4}{3}\beta\gamma^2\\ 0 & 0 & -i\frac{4}{3}\beta\gamma^2 & -\gamma^2(1+\frac{1}{3}\beta^2)\end{bmatrix}. \tag{4.2}$$

In s, the energy density U, the momentum density P_D, and the momentum flux (3,3 component) P_F may be read off from Eq. (4.2), yielding

$$U=U'\gamma^2(1+\tfrac{1}{3}\beta^2), \tag{4.3a}$$

$$P_D=-\tfrac{4}{3}\beta\gamma^2U'/c, \tag{4.3b}$$

$$P_F=U'\gamma^2(\tfrac{1}{3}+\beta^2). \tag{4.3c}$$

It should also be possible to obtain these quantities from Eqs. (3.13) and (3.14). In s', the energy density is proportional to $(T')^4$

$$U'=\sigma(T'^4). \tag{4.4}$$

In s, then we must have

$$U=\frac{1}{4\pi}\int d\Omega\,\sigma[T_e(\theta)]^4 \tag{4.5a}$$

$$=\frac{U'}{2\gamma^4}\int_{-1}^{1}d(\cos\theta)\frac{1}{(1+\beta\cos\theta)^4} \tag{4.5b}$$

$$=\gamma^2(1+\tfrac{1}{3}\beta^2)U', \tag{4.5c}$$

in agreement with Eq. (4.3a). The other quantities are similarly computed, with

$$P_D=\frac{U'}{2c\gamma^4}\int_{-1}^{1}\frac{(\cos\theta)d(\cos\theta)}{(1+\beta\cos\theta)^4} \tag{4.6a}$$

$$=-\tfrac{4}{3}\beta\gamma^2U'/c \tag{4.6b}$$

and

$$P_F=\frac{U'}{2\gamma^4}\int_{-1}^{1}\frac{\cos^2\theta d(\cos\theta)}{(1+\beta\cos\theta)^4} \tag{4.7a}$$

$$=\gamma^2(\tfrac{1}{3}+\beta^2)U', \tag{4.7b}$$

again in agreement with Eqs. (4.3).

More detailed checks with the stress-energy tensor were carried out by constructing $T_{\mu\nu}'$ for a subset, rather than all, of the photons; the expected transformation law relating $T_{\mu\nu}$ to $T_{\mu\nu}'$ was again obtained from Eqs. (3.13) and (3.14).

[7] Denoting an index running from 1 to 3 by a Latin letter, we use the following conventions: $(-T_{44})$ = energy density, (T_{i4}/ic) = density of momentum P_i; and T_{ij} = flux of momentum P_i across a surface normal to the jth axis.

V. TEMPERATURE

The conclusions of Sec. III in no way depend on the transformation properties of temperature. For our purposes, the temperature T', in s', is merely a parameter involved in the description of the photon distribution in energy, solid angle, and volume. Once the distribution is specified in s', the transformation of that photon distribution to s is completely unambiguous. It was found convenient in Sec. III to characterize the distribution in s with an effective temperature $T_e(\theta)$, defined in Eq. (3.14). It is, however, possible to define other, perhaps more meaningful, temperatures. The exponential factor in Eq. (3.13) is

$$\exp[\hbar\omega\gamma(1+\beta\cos\theta)/kT'], \tag{5.1}$$

which may be written as

$$\exp[(\epsilon-\mathbf{P}\cdot\mathbf{V})\gamma/kT'], \tag{5.2}$$

where ϵ is the photon energy, $\mathbf{P}$ is its momentum, and $\mathbf{V}$ is the velocity of the c.m. of the radiation with respect to the observer. From statistical mechanics it is known that for a slowly moving fluid the Boltzmann factor[8] is given by

$$\exp[(\epsilon-\mathbf{P}\cdot\mathbf{V})/kT], \tag{5.3}$$

which reduces to the normal $\exp(\epsilon/kT)$ for fluid velocity $\mathbf{V}=0$. If we take expression (5.3) as the *definition* of T, then $T=T'/\gamma$ in (5.2), in agreement with a recent conclusion of Møller.[9]

It is, however, perhaps even more tempting to write expression (5.2) as

$$\exp(-P_\mu V_\mu/kT), \tag{5.4}$$

where P_μ denotes the photon four-momentum and V_μ is the four-velocity of the radiation c.m. with respect to the observer $(\gamma\mathbf{V},i\gamma c)$. Expression (5.4) then is interpreted as the relativistic generalization of expression (5.3). Adopting (5.4) as the definition of temperature makes $T=T'$, a relativistic scalar. Indeed, with these definitions the photon distribution in any inertial frame is given by a very appealing formula,

$$d^6N=2\left(\frac{d\mathbf{P}d\mathbf{x}}{h^3}\right)\frac{1}{\exp(-P_\mu V_\mu/kT)-1}, \tag{5.5}$$

where T is the same in any system; T is therefore the temperature in the rest frame of the radiation. We have set $dV\equiv d\mathbf{x}$. The three factors in Eq. (5.5) are

[8] Fritz London, in *Superfluids* (Dover Publications, Inc., New York, 1964), Vol. II, pp. 95–96. We are indebted to Professor A. L. Fetter for helpful discussions on this point.

[9] C. Møller, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. No. **36**, 1 (1967).

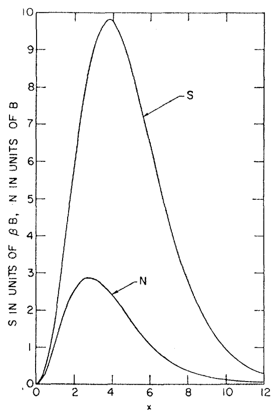

FIG. 2. The signal (in units of βB) and the noise (in units of B) of the asymmetry of blackbody radiation seen by a moving observer, as a function of $x \equiv \hbar\omega/kT$.

now interpreted, respectively, as the number of internal degrees of freedom of the photon, the number of quantum-mechanical states in phase space, and a relativistically invariant Boltzmann factor appropriate to bosons (particles with symmetric wave functions) which are not conserved.

The preceding discussion makes clear that the derivation of the blackbody-radiation distribution in a moving frame in no way depends on the transformation properties of temperature. Thus, Eqs. (3.13) and (3.14) [and, for that matter, Eq. (5.5)] give the photon distribution in a moving frame *in terms of the temperature in the rest frame*, T'. Therefore, given any definition of a transformed temperature $T=f(\beta,T')$, we can express our results in terms of this T.

VI. COSMIC 3°K RADIATION

Rewriting Eq. (3.13), we have

$$d^3N=\frac{\omega^2}{4\pi^3c^3}\frac{d\omega d\Omega dV}{\exp[\hbar\omega(1+\beta\cos\theta)/kT]-1}, \quad (6.1)$$

with the convenient definition $T\equiv T'/\gamma$. We will work in terms of the energy density U, since the product of energy density with the speed of light yields the intensity of radiation, power per unit area, which is of direct experimental interest. From Eq. (6.1) we obtain

$$d^2U=\frac{\hbar\omega^3}{4\pi^3c^3}\frac{d\omega d\Omega}{\exp[\hbar\omega(1+\beta\cos\theta)/kT]-1}. \quad (6.2)$$

It is convenient to define the dimensionless quantity

$$x\equiv\hbar\omega/kT=\gamma\hbar\omega/kT', \quad (6.3)$$

so that the energy density is given by

$$d^2U/dxd\Omega=Bx^3/(\exp[x(1+\beta\cos\theta)]-1), \quad (6.4)$$

where

$$B\equiv 2(kT)^4/(2\pi\hbar c)^3. \quad (6.5)$$

The angular dependence may be separated in a multiplicative factor, so that

$$\frac{d^2U}{dxd\Omega}=B\frac{x^3}{e^x-1}\left[1+\left(\frac{e^x}{e^x-1}\right)(e^{\beta x\cos\theta}-1)\right]^{-1}. \quad (6.6)$$

The somewhat cumbersome Eq. (6.6) is exact, with no approximations in angle or observer velocity. For the cosmic radiation it is interesting to specialize to $\beta\ll 1$, for which Eq. (6.6) becomes[10]

$$\frac{d^2U}{dxd\Omega}=B\frac{x^3}{e^x-1}\left[1-\left(\frac{e^x}{e^x-1}\right)\beta x\cos\theta\right], \quad (6.7)$$

keeping only terms of zeroth and first order in β. (Thus we assume not only that $\beta\ll1$, but that $\beta x\ll1$; to first order in β, of course, $T=T'$.) From Eq. (6.7) it is clear that $d^2U/dxd\Omega$ is a maximum (or minimum) for $\cos\theta=-1$ (or $+1$). This is expected, since the observer is moving directly toward those photons for which $\cos\theta=-1$. The angle-dependent part of $d^2U/dxd\Omega$ has a simple $\cos\theta$ form.

Defining a signal S and noise N by[11]

$$S=\left(\frac{d^2U}{dxd\Omega}\right)_{\max}-\left(\frac{d^2U}{dxd\Omega}\right)_{\min}, \quad (6.8)$$

$$N=\left(\frac{d^2U}{dxd\Omega}\right)_{\max}+\left(\frac{d^2U}{dxd\Omega}\right)_{\min}, \quad (6.9)$$

the content of Eq. (6.7) is displayed graphically[11] in Figs. 2 and 3. The signal is seen to reach a maximum in absolute magnitude at $x\approx4$, somewhat above the maximum in noise at $x\approx3$. The signal-to-noise ratio[11] continues to rise indefinitely as x increases, becoming

$$S/N\approx\beta x \quad \text{for} \quad x\gg1. \quad (6.10)$$

(It must be remembered of course that this approximation requires $\beta x\ll1$.) Explicitly,

$$S=\beta B\frac{x^4}{\cosh x-1}=2\beta B\frac{x^4e^x}{(e^x-1)^2}, \quad (6.11)$$

$$N=2B\frac{x^3}{(e^x-1}, \quad (6.12)$$

$$S/N=\beta\left(\frac{x}{1-e^{-x}}\right). \quad (6.13)$$

If, at the radial position of the solar system, the rotational velocity of our galaxy is taken to be roughly 300 km/sec, then it is reasonable to set $\beta=10^{-3}$. Thus

[10] This result, specialized to $\cos\theta=\pm1$, agrees with the corrected version of Condon and Harwit (Ref. 2).

[11] The "signal" and "noise" defined here refer only to the 3°K radiation, and take no account of formidable sources of noise with which the experimenter must cope, such as the galactic background, the sun's radiation, and the earth's atmosphere.

at the maximum in the absolute signal strength, $S/N\approx 0.4\%$. Wide-band detectors would certainly be worthwhile, particularly in the $x>4$ region. Integrating over *all* frequencies (all x) for $\beta\ll 1$, we find

$$\frac{dU}{d\Omega}=\frac{\pi^4}{15}B(1-4\beta\cos\theta). \qquad (6.14)$$

Defining a frequency-integrated signal-to-noise ratio in analogy to S/N of Eq. (6.13), we have

$$S_I/N_I=4\beta. \qquad (6.15)$$

Finally, in view of Partridge and Wilkinson's observation[2] of what appears to be a $\cos 2\theta$ effect, we can ask under what conditions such a term would be seen. From the exact Eq. (6.6), we see that expansion of the term in square brackets will involve all powers of $\cos^n\theta$; a term in $\cos^n\theta$ may be rewritten, yielding a $\cos n\theta$ term, among others. It is also clear, however, that any $\cos^n\theta$ term also involves a β^n factor. For the example discussed here ($\beta\approx 10^{-3}$) the $\cos 2\theta$ term is expected to be three orders of magnitude smaller than the $\cos\theta$ term. Alternatively, if a $\cos 2\theta$ signal were seen with $S(\cos 2\theta)/N=\delta$, we would expect a $\cos\theta$ signal with $S(\cos\theta)/N=\delta^{1/2}$, provided that $\beta\ll 1$.

VII. CONCLUSIONS

The sole effect of uniform motion through blackbody cavity radiation is to introduce an effective temperature which replaces the rest-frame cavity temperature T'. An observer is said to be in motion with respect to the cavity radiation if, in the observer's frame, the c.m. of the radiation has a nonzero velocity **V**. The effective temperature is found to be angle-dependent, being given by

$$T_e=T'(1-v^2/c^2)^{1/2}/[1+(v/c)\cos\theta], \qquad (7.1)$$

where θ denotes the angle between $-\mathbf{V}$ and the velocity of the detected photons in the observer's frame. Equation (7.1) is exact, with no approximations in the observer's speed or the photon angle.

Efforts made to detect our possible motion through the 3°K cosmic radiation depend critically on the signal-to-noise ratio of the angle-dependent radiation intensity. Assuming $v/c=\beta\ll 1$, the signal-to-noise ratio with a wide-band detector is 4β. This ratio may be improved by observing radiation at high frequencies, such that $\hbar\omega>4kT'$. Unfortunately, the absolute signal strength decreases rapidly with increasing frequency in this region. Finally, any asymmetry of the type $\cos 2\theta$ should be smaller than a $\cos\theta$ asymmetry by roughly a factor β.

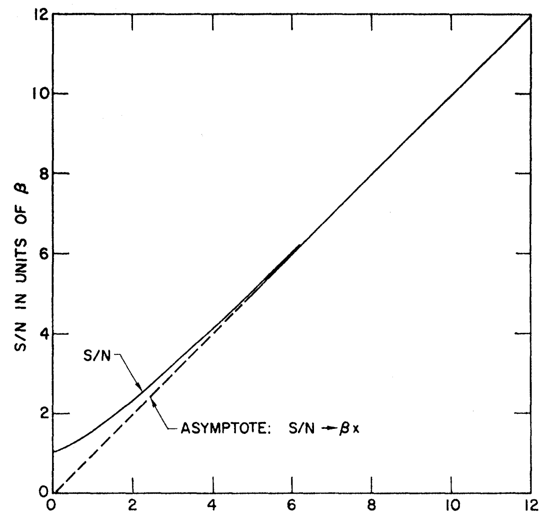

FIG. 3. The signal-to-noise ratio of the radiation asymmetry as a function of $x=\hbar\omega/kT$. This curve does not take into account any source of noise other than the blackbody radiation itself.

An interesting feature of the 3°K cosmic radiation, although it may have no cosmological implications, is the damping effect on rapidly moving bodies. Consider a black sphere of radius γ, low heat capacity, and high heat conductivity (so that there is essentially no temperature gradient in the sphere). Such a sphere, moving through the cosmic radiation, has more radiation incident on the front face than on the back face, leaving a radiation pressure imbalance. The emitted radiation is isotropic in the frame of the sphere, so that it does not contribute to the net force on the sphere. The net force is easily computed from the results of Sec. III; we find

$$F=-\tfrac{4}{3}\beta\gamma^2(\pi r^2)\left(\frac{8\pi^5}{15}\frac{(kT')^4}{(2\pi\hbar c)^3}\right). \qquad (7.2)$$

The factor in large parentheses is the energy density in the rest frame of a cavity of temperature T'. Taking $\beta=0.001$, the acceleration of the sun due to the 3°K cosmic radiation is 6.2×10^{-27} cm/sec². This would imply a relaxation time of 1.5×10^{26} yr for galactic rotation. While this is entirely negligible, we note that the temperature was presumably higher at earlier times and that the "viscosity" of the blackbody "fluid" is proportional to T'^4.

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